

Linear Motor Powered Transportation

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I. INTRODUCTION

It has been a pleasure to assemble these outstanding papers on *Linear Motor Powered Transportation: Past, Present, and Future*. This topic takes on increasing importance as we seek ways to make transport systems faster, more efficient, and more affordable. We were able to recruit outstanding engineers and managers to devote many hours to writing these papers, which come from six countries on three continents. The authors are from industry and academia, and are all experts in their field. We encouraged the authors to describe current supporting technology and linear motor systems, past history, and projections for the future. These papers have broad coverage of important ideas and can be understood by people who are not experts in the field. Many of the papers include substantial bibliographies that can be used to further explore the topics.

There are many types of linear motors, but most of those discussed in these papers are the short primary linear induction motor (LIM) and the long primary linear synchronous motor (LSM). They are similar to their rotary counterparts, but the linear versions represent a more complex design challenge. Some papers use the term *stator* for the part of the motor that is excited, but since this is sometimes on the moving vehicle, it seems better to use the transformer terminology “primary.” There is one paper on the long primary LIM. It is

This Special Issue on Linear-Motor Powered Transportation covers both supporting technologies and innovative transport systems in various parts of the World, as this technology moves from the lab to commercial operations.

possible to build a short primary LSM, but there is no paper on this topic. Unless otherwise stated, LIM refers to transport systems in which power is transmitted to the vehicle and the guideway is passive, while LSM refers to systems in which the propulsion power is supplied to windings on the guideway and no propulsion power is transmitted to the vehicle.

One important application of linear motors is the propulsion of vehicles that are suspended by magnetic fields. In 1968, Coffey coined the term “maglev” to refer to a “transport system using magnetic suspension and propulsion.” There are two common types of maglev: electromagnetic suspension (EMS), in which the vehicle is supported by attractive forces between magnets on the vehicle and a ferromagnetic structure on the guideway, and electrodynamic suspension (EDS), in which magnets on the vehicle move in the vicinity of conducting material and currents induced in the conductors react with the vehicle fields to provide lift. A key part of maglev design is integration of a linear motor propulsion system with the suspension. Either LIM or LSM propulsion can be used with EMS and

EDS, but in practice, LIM has only been used for EMS.

This issue is divided into two parts: supporting technology and transport systems. In the following two sections, we attempt to give a short synopsis of each paper.

II. SUPPORTING TECHNOLOGY

There are seven papers describing technology that is important to linear motor developers.

- 1) *Permanent magnets*: NdFeB permanent magnets are now used extensively for both rotary and linear synchronous motors, including motor designs described in this issue. Thompson has had considerable experience in designing these magnets into linear motor and magnetic brake applications. His paper clarifies important issues in the application of permanent magnets.
- 2) *LIM control*: Control of linear motors is similar to control of rotary motors, but there are important differences. Meeker and Newman's paper is based on their work in developing a control system for an LIM launch system for U.S. Navy aircraft carriers. The resulting linear motor has the highest acceleration rate and peak power demand of any linear motor in operation today.
- 3) *LSM control and block structure*: Linear synchronous motors for transport must be broken into segments, or blocks, each with its own position sensing and control. Perreault has had extensive experience in developing LSM control systems, and his paper provides valuable insights into the design of the block structure and control algorithms.
- 4) *Multilevel converters*: Inverters and four quadrant recti-

fiers are now being used to provide excitation of linear motors. At high power levels, the most cost-effective solution is to use several lower power modules with outputs combined to produce higher power than is possible with commercially available lower power modules. The authors of this paper have created an excellent introduction to a topic that is important in high-power linear motor applications.

- 5) *Modeling and simulation*: Tools for modeling and simulation have improved dramatically over the approximately 40-year history of major linear motor development. It is doubtful if modern designs would be as effective as they are without these tools. Dudgeon *et al.* provide an example of simulation with some comments on future possibilities in the era of multiprocessing.
- 6) *High-temperature superconductors*: Superconductors have been used in several maglev designs, and the improved performance of the latest high-temperature superconductors could lead to substantial improvement in high speed transport systems. Hazelton and Selvamanickam describe some of the latest ideas in this evolving field.
- 7) *Ultracapacitor*: This relatively new type of capacitor can store exceptionally large amounts of energy and deliver very high peak powers. Ultracapacitors are used in electric vehicles and have promise for linear motor drives. The authors of this paper have developed some promising new ideas for increasing the performance of these capacitors.

Supporting technologies are described in many other IEEE publica-

tions. The April 2007 Special Issue on Electric, Hybrid Vehicles is particularly recommended. It includes papers on electrical machine drives, power converters, semiconductor power devices, batteries, and ultracapacitors.

III. LINEAR MOTOR SYSTEMS

There are eight papers that describe existing linear motor powered transport systems that are either operational or in a development phase.

- 1) *Pipeline*: Montgomery *et al.* describe a unique way to move coal with hopper cars in a pipe using linear motor propulsion. The linear motor allows rapid movement of large amounts of material with the potential to climb steep grades, and be efficient, and cost-competitive compared with conventional ways of performing this task.
- 2) *Personal rapid transit (PRT)*: A PRT system is now being installed at Heathrow Airport, and several companies are developing other versions. Most PRT designs use rotary motor propulsion, but Vectus uses a long stator LIM. Gustafsson describes the design and operation of this unique linear motor.
- 3) *Urban maglev*: General Atomics (GA) has worked for several years to develop a maglev system optimized for use in urban areas at speeds up to 161 km/h (100 mph). Their design uses permanent magnets for an electrodynamic suspension with LSM propulsion. Gurol describes the GA design with thoughts on future applications of the technology.
- 4) *Maglev in China*: China has installed a high-speed Transrapid maglev system between Shanghai and Pudong Airport. This is the only operational high-speed maglev

system, and China has active plans for other installations. Yan describes maglev and linear motor developments in China, including a discussion of future opportunities for these technologies in China.

- 5) *Superconducting maglev*: Japan has worked for many years to develop a superspeed maglev system using superconducting magnet EDS with LSM propulsion. The design has been tested at speeds up to 581 km/h, and commercial operation at a maximum speed of 550 km/h is planned to start in 2025. Sawada describes this design and future development plans.
- 6) *Korea urban maglev*: Korea has constructed an urban maglev test facility and is actively working on a project to install this system between Seoul, South Korea, and Incheon airport. This design uses EMS suspension and LIM propulsion with a maximum operating speed of 110 km/h. Park *et al.* describe

this system and plans for installation by 2012.

- 7) *Linear motor overview*: A 30 km installation of the German Transrapid system is now operational in Shanghai, China. This system, referred to in (4), is the only commercially operating high-speed maglev design, but there are active plans for other installations. Hellinger and Mních have been involved in this development, and in this paper, they provide an overview of types of linear motors and their applications with specific reference to maglev systems.
- 8) *Urban maglev*: MagneMotion is the second U.S. company that is supported in part by the Federal Transit Administration to develop an urban maglev system. In this paper, Thornton describes the MagneMotion M3 maglev system and opportunities for efficient and affordable maglev in the United States.

There are other operating and development linear motor transport systems that are described on the

Internet. Particularly noteworthy is the Bombardier Advanced Transit System that uses LIM propulsion with a steel wheel on steel rail suspension. Their design has demonstrated the advantages of linear motor propulsion in many applications throughout the world.

IV. CONCLUDING THOUGHTS

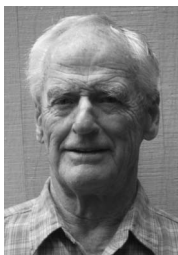
There are many other papers that would be appropriate to this Special Issue, and omission of these papers does not in any way reflect on the importance of other technologies or system designs. The important conclusion is that linear motor power transportation is finally moving from the laboratory to commercial operation, and we can expect greatly increased interest by the IEEE community.

All of the topics discussed in this issue can be studied in substantial depth on various Internet sites. Searching terms like *linear motor*, *maglev*, and *innovative transportation* will lead you to these sites. We encourage readers with good ideas on these topics to submit papers to the IEEE for publication. ■

ABOUT THE GUEST EDITORS

Richard Thornton (Life Fellow, IEEE) received the B.S. degree in electrical engineering from Princeton University, Princeton, NJ, and the S.M. and Sc.D. degrees from the Massachusetts Institute of Technology (MIT), Cambridge.

He was on the Faculty at MIT for more than 40 years before retiring and helping found MagneMotion Inc. He has worked on maglev and linear motor development since 1968, including work on high-speed electrodynamic systems and electromagnetic systems with a focus on long stator linear synchronous motor propulsion. This work has included participation in an MIT team supported by the National Science Foundation to develop the Magneplane; work on a team with Bechtel, MIT, GM, and Draper Laboratories with support from the Federal Railway Administration as part of the National Maglev Initiative; and work at MagneMotion supported in part by the Federal Transit Administration as part of the Urban Maglev Project. He is author or coauthor of more than 20 papers on linear motors and maglev. He has received 21 patents, mostly in the field of linear motors and maglev.



Marc T. Thompson (Member, IEEE) was born on Vinalhaven Island, ME, in 1963. He received the B.S., M.S., electrical engineer's, and Ph.D. degrees from the Massachusetts Institute of Technology (MIT), Cambridge, in 1985, 1992, 1994, and 1997, respectively.

He specializes in custom R/D, analysis, and failure investigations into multidisciplinary electrical, magnetic, and electronic systems with Thompson Consulting, Inc., Harvard, MA. He was a Consultant for Magnemotion, Magnetar, and Magplane, among other companies, following his doctoral work in maglev at MIT. He was a Consultant designing electric motors and generators and has worked for the U.S. Department of Transportation evaluating maglev and linear motor technologies worldwide. He is an Adjunct Professor at Worcester Polytechnic Institute, Worcester, MA, where he teaches graduate-level courses in analog, power electronics, magnetic design, electric motors, and power distribution. He is the author of *Intuitive Analog Circuit Design* (Amsterdam, The Netherlands: Elsevier, 2006) and coauthor (with A. Kusko) of *Power Quality in Electrical Systems* (New York: McGraw-Hill, 2007). He is a contributor of three chapters to *Analog Circuits (World-Class Designs)* (Amsterdam, The Netherlands: Elsevier, 2008) and one chapter to *Portable Electronics (World Class Designs)* (Amsterdam, The Netherlands: Elsevier, 2009). He has received seven U.S. patents and is a Firefighter with the Harvard, MA, Fire Department.



Brian M. Perreault (Member, IEEE) received the B.S. degree in computer engineering from Boston University, Boston, MA, and the S.M. and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge.

He is a Cofounder of MagneMotion, where he is Vice President of Controls, and an expert in microprocessor-based control systems. He is responsible for control system development efforts. Previously, he was a Head Teaching Assistant while completing his doctoral work at MIT.

Dr. Perreault is a member of Tau Beta Pi. He received a number of grants and awards during his college tenure, including a National Society of Professional Engineers Scholarship, Mortar Board Outstanding Student Award, National Science Foundation Graduate Fellowship, Eisenhower Transportation Graduate Fellowship, Frederick C. Hennie III Teaching Award, and J. K. Dixie Howell Outstanding Paper and Presentation Award. He won first place in an IEEE/M2C VLSI Design Contest.



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He was a Postdoctoral Fellow with the Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology (MIT), Cambridge, in 2002 and then a Visiting Scientist with the MIT Plasma Science and Fusion Center. He has been an Electrical Engineer with Magplane Technology, Inc., since 2007. His main research contributions during the past 16 years have included maglev trains, linear drives, pipeline transportation, and superconducting magnets. He was an Administration Officer with the Maglev Office, Ministry of Science and Technology of China, in 1999–2001. He was a national maglev expert and a Review Committee Member for the maglev project of the National 863 High-Tech Plan.

